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Review on development and demonstration of hydrogen fuel cell scooters

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ABSTRACT

The current development of fuel cell scooters has been reviewed in this paper. Fuel cell scooters, by nature, have zero emissions, and they have the potential to replace current petroleum-propelled engine scooters. First, the fundamentals of fuel cells, including the critical technologies pertaining to fuel cell engines and hydrogen storage, were introduced. Then, the technical feasibility of fuel cell scooters was discussed in parallel with the hydrogen infrastructure model. The accomplishments of fuel cell scooters in Taiwan were presented. Moreover, the contribution of replacing petrol scooters by hydrogen fuel cell scooters to reduction in greenhouse gas (GHG) emission and energy conservation was evaluated. Furthermore, industrial competition with regard to the development of fuel cell scooters was discussed on the basis of a strengths, weaknesses, opportunities, and threats (SWOT) analysis. In conclusion, with mature fuel cell technology together with solid foundation of the scooter industry, Taiwan offers conditions that were conducive for the development of fuel cell scooters. Its social and technical capability will be proved on account of the leading demonstrations of fuel cell scooters in the world. If it can develop a successful business model, Taiwan could enjoy the advantages of tapping the huge global market for zero-emission scooters.

Contents

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1. Introduction

From the viewpoints of global warming and the inevitable depletion of fossil fuels, the development of an alternative source of energy for automobiles is exceedingly important. Hydrogen is considered to be a viable substitute for petroleum in the transport sector, and therefore, hydrogen-fueled fuel cell vehicles are being seriously considered by automakers [1–4].

Almost all major automakers of the world have unveiled fuel cell vehicles in the past few years, for example Honda FCX Clarity [5], Toyota FCHV [6], Mercedes-Benz F-Cell [7], and Chevrolet Equinox Fuel Cell [8,9]. Most of the automakers are planning to enter the fuel cell vehicle market around 2015. Nowadays, these candidate vehicles are in the social demonstration phase; in this phase, the feasibility of driving the vehicles in real-world conditions is examined. For example, the US Department of Energy (DOE) initiated the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" [10–12] in 2004, which is the largest project of its kind in the world; the objective of the project was to demonstrate fuel cell vehicles and the supporting refueling infrastructure in parallel, under real-life conditions. This seven-year project involves multiple geographic locations and climates with a variety of hydrogen sources, including renewable and fossil fuels. It also identified and tracked the status of technologies as they evolved, assessed toward technology readiness, and provided feedback for research and development activities pertaining to the use of hydrogen as an alternative source of energy. To date, 152 vehicles have been employed, 24 hydrogen-refueling stations have been set up, and a distance of over 3 million miles has been traveled by hydrogen-fueled fuel cell vehicles. The key objectives of the project are to evaluate fuel cell durability, vehicle-driving range, and on-site hydrogen production cost. In this project, the National Renewable Energy Laboratory (NREL) has a role that involves gathering extensive data from the systems and components under real-world conditions, analyzing these detailed data, and then comparing the obtained results to the target results. While the raw data are regarded as confidential by the NREL, analysis results are aggregated into public results called composite data products (CDPs). These public results show the status and progress of the technology, but do not identify individual companies.

In Japan, the "Japan Hydrogen Fuel Cell Project (JHFC)" was initiated in 2002, and it involved activities related to hydrogen fuel cell vehicles [13–15]. The second phase of the JHFC project ended in 2010, and thereafter, preparations for the commercialization of hydrogen fuel cell vehicles began. Over a period of eight years, 135 passenger cars that have covered a combined distance in excess of 1 million km and 13 buses that have traveled more than 400,000 km have been tested. The project reported bench test efficiencies of 60% and an on-road fuel economy of up to 70 miles/gallon gasoline equivalent (gge) for the latest passenger cars. In general, the project has improved the performance of fuel cell electrical vehicles [16], achieving the 2015 targets for the driving range, efficiency, low-temperature performance, and refueling time, while vehicle durability and vehicle cost remained focus areas. After the JHFC project, a coalition of 13 major Japanese automakers and energy companies, including the likes of Toyota, Honda, and Nissan, joined hands in early 2011 to begin selling the hydrogen fuel cell vehicles by 2015 and to develop a hydrogen supply network extending throughout Japan [17]. With help from the JHFC project, twelve stations were already in service. Japan's Hydrogen Highway plans to set up 100 refueling stations by 2015 [18].

Generally, a sedan is equipped with a fuel cell engine rated higher than 30 kW [20–22]. Considering the indigenous technology level and limited resources, Taiwan should not duplicate efforts with regard to the development of the aforementioned fuel cell passenger cars because of limited technologies and resources. Taiwan has made a strategic decision to focus on the development of niche products in the fuel cell industry [23]. Actually, Taiwan has the opportunity of being the global leader in the development and manufacture of two-wheel vehicles such as scooters and wheelchairs, which would be the domestic niche industry. In addition, in Taiwan's sustainable transport strategy, the electric scooter plays an important role since it is regarded as the next best option after the petrol scooter for personal commuting [4,24]. The lead-acid battery had been the major power source for the electric scooter. However, due to the shortcomings of insufficient driving range, heavy in weight, lack recharge stations, and high price, it was not competitive on the market. Low-temperature proton exchange membrane (PEM) fuel cells have the attributes of rapid start-up and high power density, which make it the ideal power source for electric scooters. Several Taiwan-based companies have been developing PEM fuel cell engines for electric scooters for years. They have finished several generations of prototypes of fuel cell scooters. The performance of these prototypes has been tested and verified by third parties as well. Nowdays, a learning demonstration program for fuel cell scooters and a hydrogen infrastructure in real-world conditions is under way [19]. It involves the social demonstration of the whole range of solutions for fuel cell scooters, including domestic fuel cell technologies, onboard hydrogen storage, and hydrogen infrastructure. The results of the program are expected to help policy makers in making decisions pertaining to the commercialization of fuel cell scooters industry.

This paper presents a comprehensive review of the development and demonstration of fuel cell scooters. First, the technical feasibility of fuel cell scooters was acclaimed, including the critical technologies used in fuel cell engines and the hydrogen infrastructure model. The accomplishments of fuel cell scooters in the world, particularly in Taiwan, were introduced as well. Then, the contribution of replacing petrol scooters by fuel cell scooters to the reduction in greenhouse gas (GHG) emission and the improvement in energy efficiency was evaluated. Moreover, an analysis of the strengths, weaknesses, opportunities, and threats about Taiwan's competitiveness in the global market of fuel cell scooters was provided. If it can develop a successful business model, Taiwan could enjoy the advantages of tapping the huge global market for zero-emission scooters.

2. Technology validation

A functional block diagram of the fuel cell engine used in fuel cell scooters was shown in Fig. 1. The support components of the fuel cell engine included a PEM fuel cell stack, a membrane humidifier, a metal-hydride canister, an air blower, a DC/DC converter, and a microcontroller. The PEM fuel cell stack was the core of the engine, which used pure hydrogen (>99.9%) [25]. As shown in Fig. 1, pure hydrogen from the metal-hydride canister flowed into the fuel management subsystem entered the fuel cell stack, returned to the subsystem through the stack anode exit, and recirculated into the hydrogen pipeline. The bypass of the anode exit was equipped with a solenoid valve to conditionally expel the inert gas. As further shown in Fig. 1, a blower drove air into the cathode pipeline through a specially designed filter to keep the system free from dust and oil. A load-following technique was employed in the design of the oxidant supply subsystem. The microcontroller was capable of monitoring the sensors measuring the voltage, current, temperature and pressure. It also appropriately drove the external devices such as the air blower, solenoid valve, water pump, and cooling fan. Accordingly, the development of the above major components of the fuel cell engine was described in detail as follows.

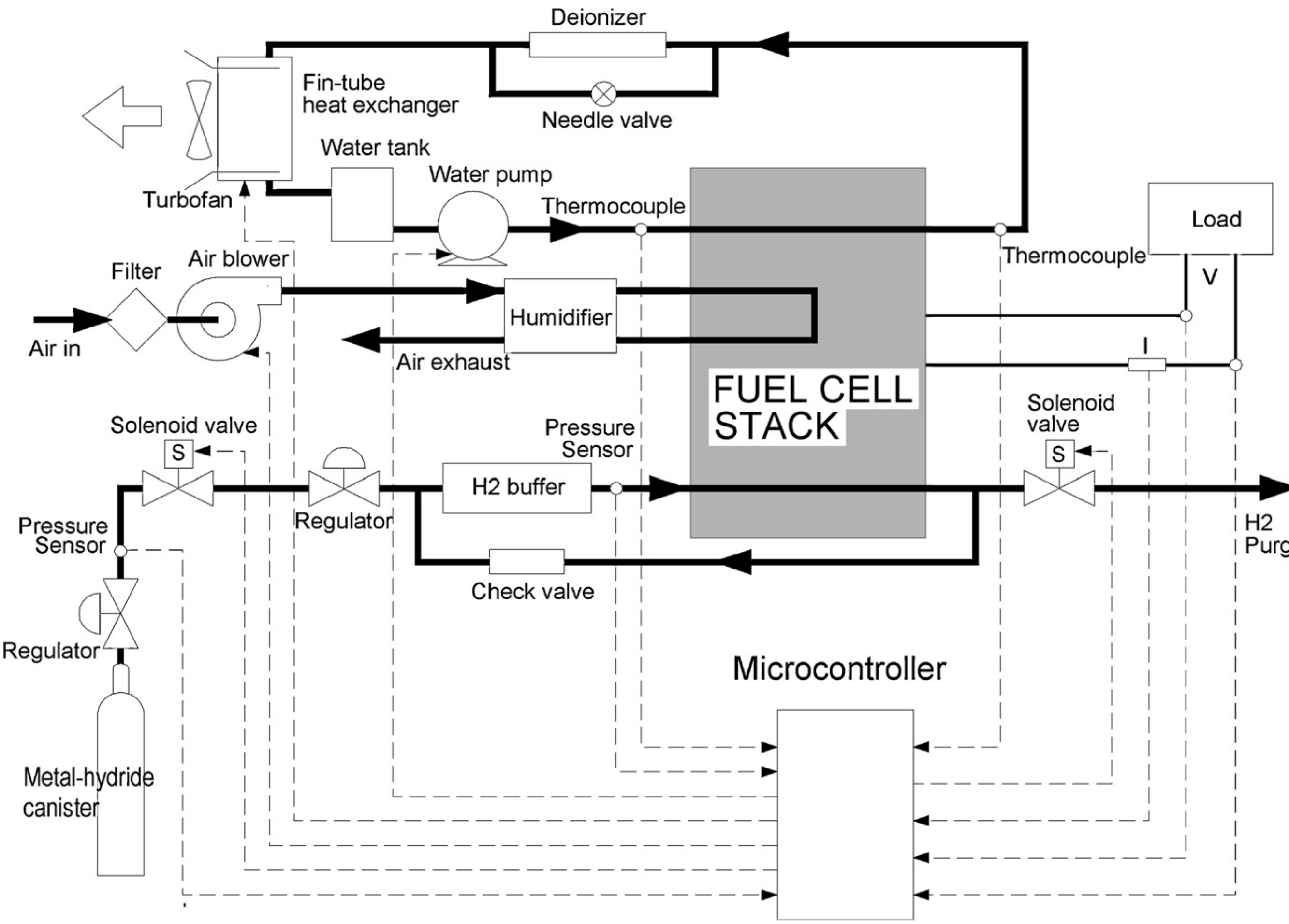

Fig. 1. Block diagram of the fuel cell engine for scooters.

2.1. Fuel cell stack

The number of cells decides the stack voltage, while the active area of the MEA decides the maximum current through the stack.

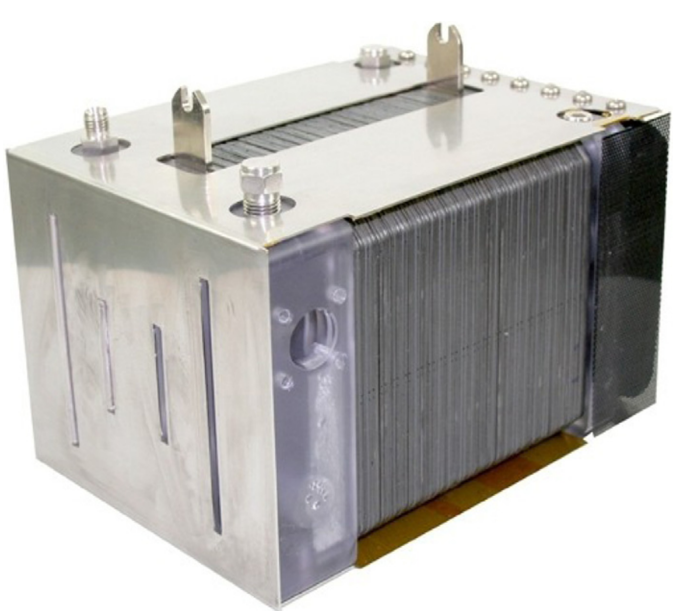

Fig. 2. Fuel cell stack for scooters.

The fuel cell stack to propel the electric scooter was shown in Fig. 2, which has 36 cells in series and 150 cm^2 in the active area. The polarization curve of the fuel cell stack was shown in Fig. 3 and other details of the stack were summarized in Table 1. It is noteworthy that the stress distribution on the fuel cell is very important in the stack design. Uneven stress distributions mean high contact resistances. They will cause local hot spots on the cell surfaces that results in the fuel leakage and thus damages the fuel cell. To ensure good contact between each cell, using the in-box alignment technology assembles the fuel cell stack instead of the conventional pack using bolt screws [22,25], as shown in Fig. 2.

In addition, before entering the fuel cell stack, the air should be appropriately humidified to ensure higher power generation efficiency and longer life of the fuel cell stack. Fig. 4 shows the membrane humidifier used for the fuel cell stack. Its performance was listed in Table 2. The performance was evaluated by measuring the relative humidity of fresh air passing through the membrane humidifier under the real operational conditions. The primary flow was the fresh air from the ambient while the secondary flow was the cathode exhaust gas. The stoichiometry of the cathode flow was fixed at 2.5 while the dew point of the cathode exhaust gas was fixed at 60 °C. The fresh air entering the humidifier had a temperature of 25 °C and relative humidity of 20%. It is seen from Table 2 that the relative humidity of the humidified air did not affect by the flow rate essentially, which was ranged from 95.1% to 97.1%. It is notable that the pressure drop across the membrane humidifier was increased with the increase of the flow rate, meaning that the higher drag required more

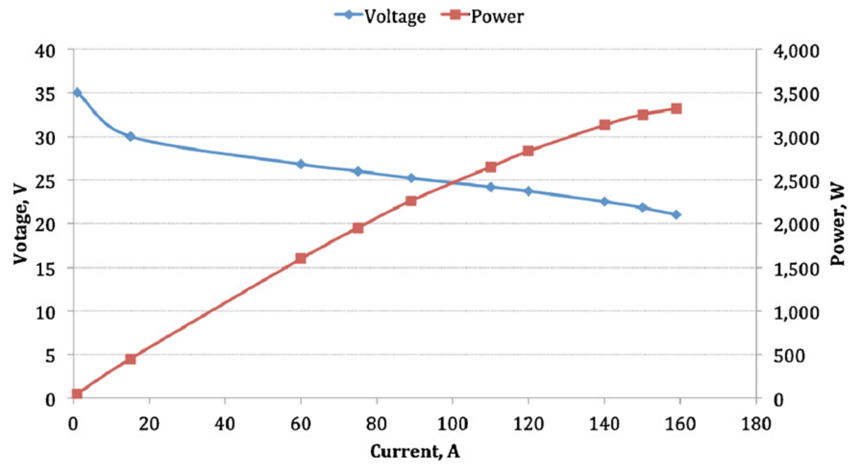

Fig. 3. Polarization curve of the fuel cell stack.

Table 1
Specifications of the fuel cell stack.

Nominal output voltage	26 VDC
Environment temperature	20–40 °C
Operation output voltage range	22–34 VDC
Rated output current	70 A
Rated power	1900 W
Output current	150 A (for 30 s)
Peak power	3200 W

Fig. 4. Membrane humidifier for the fuel cell stack.

pumping power to drive the cathode air under higher power conditions.

2.2. Metal hydride canister

The hydrogen was stored in a canister containing $LaNi_5H_6$ metal-hydride powders (as known as AB5 alloy), as shown in Fig. 5(a). It was recognized as the safest hydrogen storage method with storage pressure of less than 10 bars. The internal structure of the aluminum canister was designed for improvement of heat transfer inside the canister [26,27]. During the electrochemical reaction in the fuel cell stack, waste heat was produced. On the contrary, the metal hydrides absorbed heat while discharging hydrogen. Hence, the heat generated by the fuel cell stack could be recycled to heat the metal hydride canister. As shown in Fig. 5(b),

Table 2
Performance of the membrane humidifier.

Flow rate (slpm)	Pressure drop (mbar)	Pressure drop (in H_2O)	Temperature (°C)	Humidification (RH)
53.8	2.9	1.16	51.7	96.5–97
107.6	8.1	3.25	52.0	97–97.2
161.4	14.9	5.98	50.1	96
215.2	23.9	9.59	49.7	95.5–96.5
350	45.7	18.3	47.4	95.1

(a)
(b)
(c)

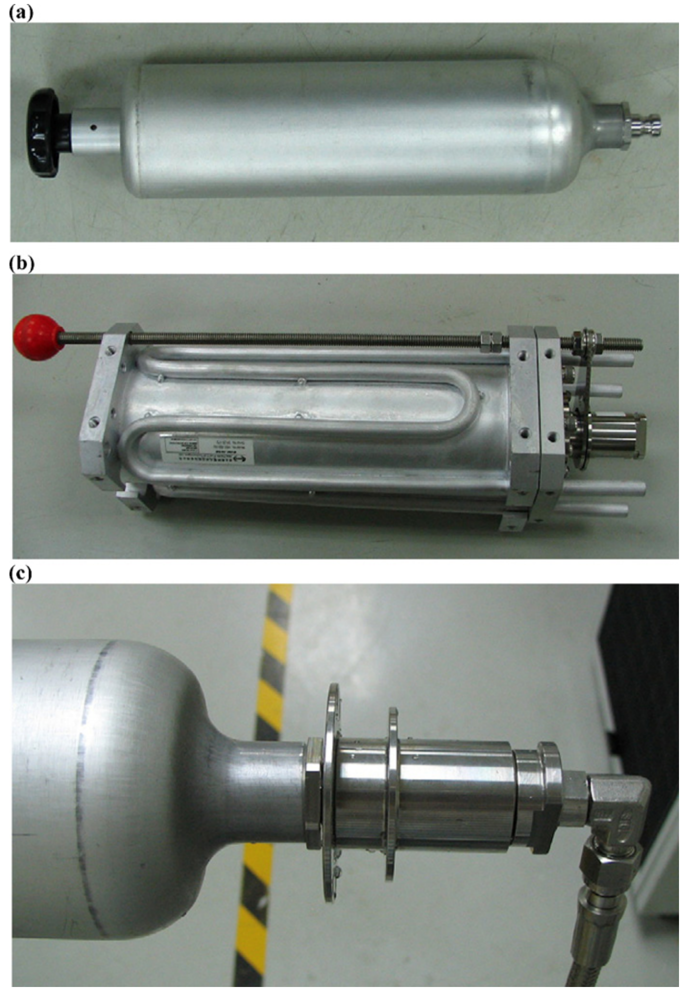

Fig. 5. (a) Metal-hydride canister, (b) water jacket for the canister, and (c) quick connecter on the canister.

Table 3
Characteristics of the metal hydride in the aluminum canister.

Hydrogen storage capacity	45 g/Canister
Canister material	Aluminum 6061-T6 alloy
Canister dimension	Diameter 76 mm; Length 365 mm
Safety protection	Over pressure relief valve (580 psig)
Metal hydride material	AB5 alloy
Hydrogen purity requirement	>99.99%; O_2, CO, S < 1 ppm
Charging pressure	140 psig @ 10–20 °C
Hydrogen discharge rate	>45 g/Canister @ 8.0 slpm, 50 °C >39 g/Canister @ 16.0 slpm, 50 °C
Weight	4.4 ± 0.1 kg/Canister

the metal hydride canister was enclosed in a designed water jacket. Actually, the water jacket had ever been widely used to cool the barrels of machine guns and internal combustion engines. Here, it was employed to heat the metal hydride canister. Water-filled tubes wound the water jacket. The metal sheath having intake and outlet vents allowed water to be pumped through the tubes. The flow of hot water from the stack coolant outlet precisely controlled the temperature of the water jacket. It provided sufficient heat capacity to meet the thermodynamics of hydrogen discharge from the metal hydride canister.

As shown in Table 3, the hydrogen storage capacity of the metal-hydride canister was 45 gH2, which was equivalent to 1.1% in weight percentage. When the hydrogen flow rate was lower than 8.2 slpm at 50 °C, the hydrogen in the canister was discharged totally (i.e., 45 gH2). However, as the hydrogen flow rate was larger than 15 slpm at 50 °C, the hydrogen discharge rate of the canister was only 39 gH2.

It is interested to note that when hydrogen in the canister was being depleted, the empty canister was replaced by a filled one but was not in situ refilled with hydrogen. Therefore, the canister was equipped with a quick connect/disconnect connector for easy replacement. Fig. 5(c) shows the quick connector between the metal-hydride canister and the feeding line of the anode of the fuel cell stack.

2.3. Air blower

Air blowers play key roles in the design of a fuel cell engine. Their efficiency and performance are vitally important in the operation of fuel cell systems and are a critical factor in maximizing the overall efficiency of a system. A high-efficiency blower has a lower parasitic load on the system and may allow for a reduced fuel cell stack and lower power inverter costs. The proper matching of a motor's speed/torque curve to its aerodynamic output is especially important in increasing efficiency thereby reducing its demand on a fuel cell system. The airflow rate was dependent linearly on the speed of the blower, which was controlled by using the PWM scheme. According to the specification of the fuel cell engine, the air blower has been developed and tested at various operation conditions as listed in Table 4.

Table 4
Characteristics of the air blower.

Pressure (kPa)	Flow rate (l/min)	Current (A)	Voltage (VDC)	Power (W)
4.5	309.3	3.7	24	88.8
4.6	259.3	3.5	24	84
4.7	220.4	3.4	24	81.6
4.8	138.8	3.0	24	72
4.9	119.6	3.0	24	72
5.0	117.3	3.0	24	72
5.2	91.1	3.0	24	72
5.3	41.8	3.0	24	72

2.4. DC–DC converter

The main feature of this technology is to control charging current of the DC/DC converter at different state of charges (SOCs) of the secondary battery and to prevent overcharge of the secondary battery. It also ensures that the fuel cell could operate at the best voltage with the best operation efficiency. The DC/DC converter developed herein could control output voltage of the fuel cell engine and boost the bus voltage to the level that was required by the motor and to charge the secondary battery. This DC/DC converter transfers power between different voltages of the fuel cell and the secondary battery by tracking their voltage separately at the same time and applying PWM control schemes. This made the efficiency of the DC/DC converter higher than 90% at the operation power up to 1200 W.

2.5. Microcontroller

Controlling the operation of the fuel cell scooter requires a smart microcontroller together with the proper algorithm that safely starts, monitors and shuts down the fuel cell scooter under all operating conditions. In the fuel cell scooter, an Intel 8051 microprocessor acted as the head of the system. As shown in Fig. 1, the microcontroller was capable of monitoring the sensor signals of voltage, current, temperature, and pressure. It also took appropriate actions in order to drive the external devices such as the air blower, the solenoid valve, the water pump and the cooling fan. A remote LCD display located on the scooter board was interfaced with the microcontroller in order to monitor the output of the system. In addition, the voltage of each cell within the fuel cell stack was monitored in a multi-channel analog multiplexer in order to detect individual cell failures. Custom-built analog isolation amplifier circuits were used to isolate the microcontroller from the fuel cell stack's high voltage output. In the event of a shutdown, the microcontroller stored the current system parameters. These parameters could be downloaded to the personal computer through the RS232 communication port on the microcontroller.

2.6. Motor and transmission system

A DC brushless motor was used to propel the fuel cell scooter. The performance curve of the driving motor was shown in Fig. 6. The maximum power of the motor was 4.0 kW at 4400 rpm. A half-load mode function of motor was designed into controller to protect the fuel cell stack and the secondary battery in case there are any abnormal situations. Two-speed transmission system was employed in the scooter, which was obtained from the commercial market. The test results showed that using this transmission system to match with the motor could increase the torque at low speed climbing without scarifying the maximum speed performance. The transmission switched from first to second speed when the scooter speed is over 30 km/h.

3. Hydrogen infrastructure

Hydrogen is widely used for its chemical properties in a range of industrial applications. Fuel cells that use direct hydrogen are opening up a new business opportunity for hydrogen suppliers – one with potentially high demand if some key markets take off. The key direct hydrogen fuel cell applications that are currently seeing traction are light duty vehicles, forklifts, buses, stationary power, and scooters. These fuel cell markets present different infrastructure build out pathways, with varying opportunities and challenges.

There is no one clear business model for the hydrogen infrastructure market at present. Currently, the major players in hydrogen fueling are large multinationals: the industrial gas companies, and

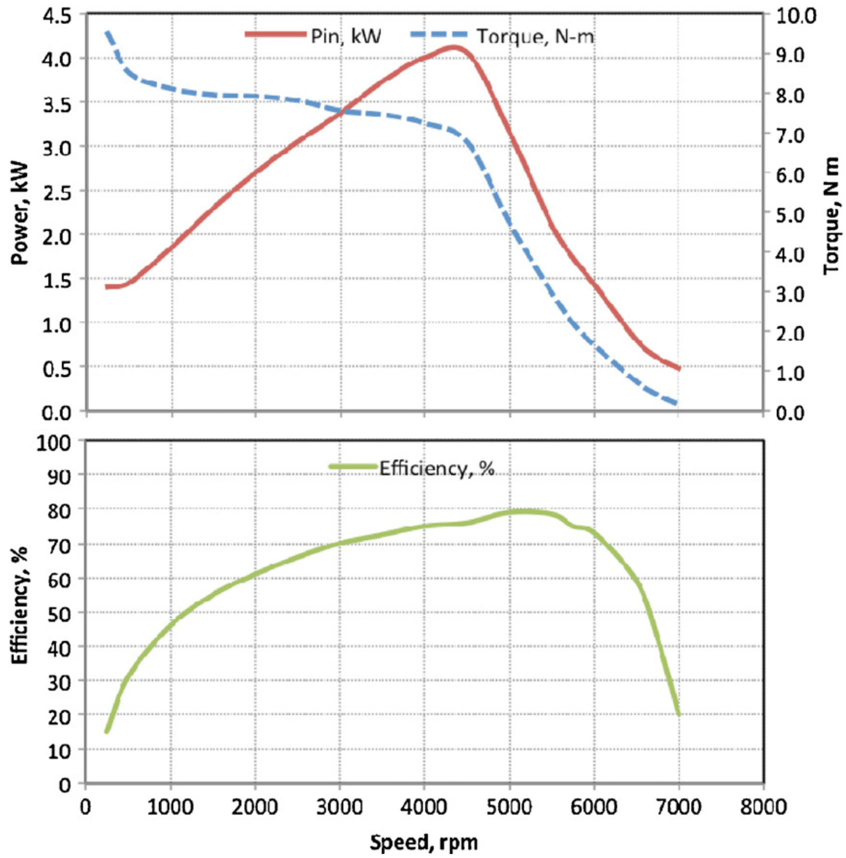

Fig. 6. Performance curve of the propelled motor.

the energy and gas companies, both those that operate retail gas stations and those that provide fuels for the grid. These companies tend to favor large-scale hydrogen infrastructure options. Some smaller "independent" hydrogen suppliers that are developing and marketing smaller onsite hydrogen generator technologies could offer a more modular path to hydrogen infrastructure build out. Yet another pathway is presented by vehicles using very small quantities of hydrogen, such as scooters. These vehicles can be fueled by small solid-state hydrogen cartridges, which are readily distributed in retail outlets.

Many hydrogen-storage technologies have been developed for vehicular applications [28–32], such as compressed hydrogen [33], liquid hydrogen [34–36], onboard reforming hydrogen [29,37], chemical hydride [38,39], and metal hydride [40,41]. Table 5 summarized the matrices of the energy density, convenience, cost, and safety of the hydrogen-storage technologies in vehicular applications. Both the energy density and safety of compressed hydrogen are low, and the fuel will occupy considerable space in scooters. Although liquefied hydrogen has a high energy density, its safety is low and its cost is high. In the past, automakers have conducted extensive research on hydrogen production from fossil fuel through onboard reforming, using fuels such as petroleum for GM's S-10 pickup [42] and methanol for DaimlerChrysler's NECAR-5. However, the weight of a scooter and the space available in it limit the storage of this kind of fuel. In addition, the reforming reaction takes place at high temperatures, resulting in the start-up time of the scooter being long. The metal hydride does not catch fire easily in the case of hydrogen leakage since it shows endothermic characteristics during hydrogen release. In addition, even with when shot with a bullet, the metal hydride canister that was fully charged with hydrogen only melted in the area surrounding the bullet hole and did not explode [43]. Therefore, on the basis of technology matrices of the energy density, convenience, cost, and safety of hydrogen storages, the metal hydride appears to be the most promising material for storing hydrogen for use in fuel cell scooters.

Table 5
Relative rating for scooter application of various storage schemes.

	Energy density	Convenience	Cost	Safety
Compressed Hydrogen	Low	Low	Low	Low
Liquid Hydrogen	High	Low	High	Low
Reforming	High	Low	Medium	Medium
Metal hydride	High	High	Low	High

Fig. 7 shows the hydrogen infrastructure for fuel cell scooters. It is quite similar to the exchange model of gas cylinders commonly used in many households in Taiwan. The canisters are designed with quick connectors to allow easy replacement. As shown in Fig. 8, when hydrogen in canisters is being depleted, rather than refilling the empty canisters with hydrogen, the riders drive their scooters to the exchange stations for exchanging the empty canisters with filled ones. Once the new canisters are plugged in, the riders can immediately continue driving their fuel cell scooters, similar to the case of refueling conventional ICE scooters. The whole process of changing canisters takes less than 30 s, and most importantly, the riders do not come in direct contact with hydrogen in the process. As shown in Fig. 7, the empty metal hydride canisters are returned to the hydrogen factory. All hydrogen canisters will be refueled with hydrogen in a central facility before being delivered to the exchange stations. Distribution companies transport the full/empty metal hydride canisters between the exchange stations and the hydrogen (production) factory. The exchange stations may be located at gas stations, scooter repair centers, or at points in the existing retail network.

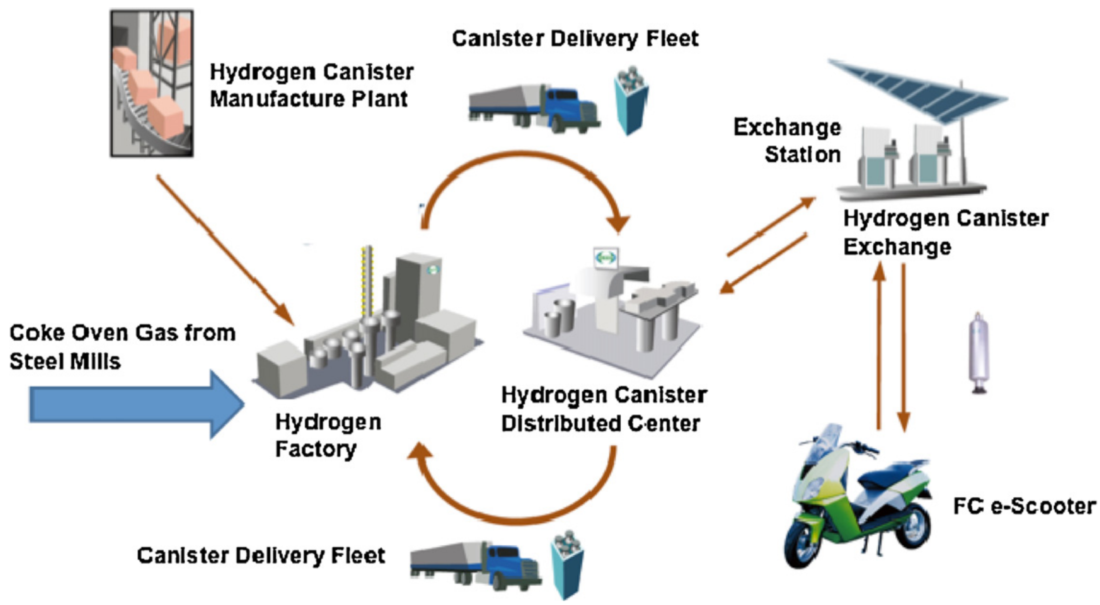

Fig. 7. Hydrogen infrastructures of fuel cell scooters.

In general, the technologies for producing, storing, and transporting hydrogen are mature. According to the data obtained from manufacturers [24], as shown in Table 6, each canister contains 45 gH2 (about 500 l) that can be used for driving a distance of 30–40 km depending on the driving conditions. Each scooter can carry two metal hydride canisters. If the annual driving distance of each scooter is 5000 km, the hydrogen consumption is about 71 m^3/year. The number of fuel cell scooters on the road is estimated to be 100,000 units soon after the launch of the scooters. Therefore, the additional hydrogen consumed by fuel cell scooters would be less than 6.25 million m^3/year, which is less than 10% of the current hydrogen market in Taiwan. Therefore, supply of hydrogen for fuel cell scooters is quite abundant.

Fig. 8. Situation of exchange metal hydride in the exchange station.

4. Perspectives of fuel cell scooter

4.1. Global competition

Fig. 9 shows the development of fuel cell scooters in Taiwan. Some international brands are also included for the sake of comparison, such as Yamaha [44], Honda [45], Intelligent Energy [46], and Suzuki [47]. It is seen that the research and development stage extended from 1999 to 2004. The second stage was from 2005 to 2010, during which the technology of fuel cell scooters was validated. The third stage in the development of fuel cell scooters commences in 2011. In this stage, the pre-commercialization public demonstration of fuel cell scooters will be carried out.

Table 6
Specifications of the fuel cell scooter.

Dimensions	1576 mm × 440 mm × 1087 mm (*L* × *W* × *H*)
Motor type	DC brushless motor
Weight	120 kg (curb weight)
Transmission	Timing belt
Front wheel	3.0–10″
Nominal voltage	24 V
Rear wheel	3–10″
Maximum current	70 A
Maximum speed	50 km/h
Fuel	Hydrogen
Climb	10 km/h @ 10°
Fuel storage	Metal hydride
Fuel consumption	1.2 gH2/km @ 30 km/h
Refuel	Canister exchange
Range	75 km @ 30 km/h; 50 km @ city mode
Refuel time	<30 s

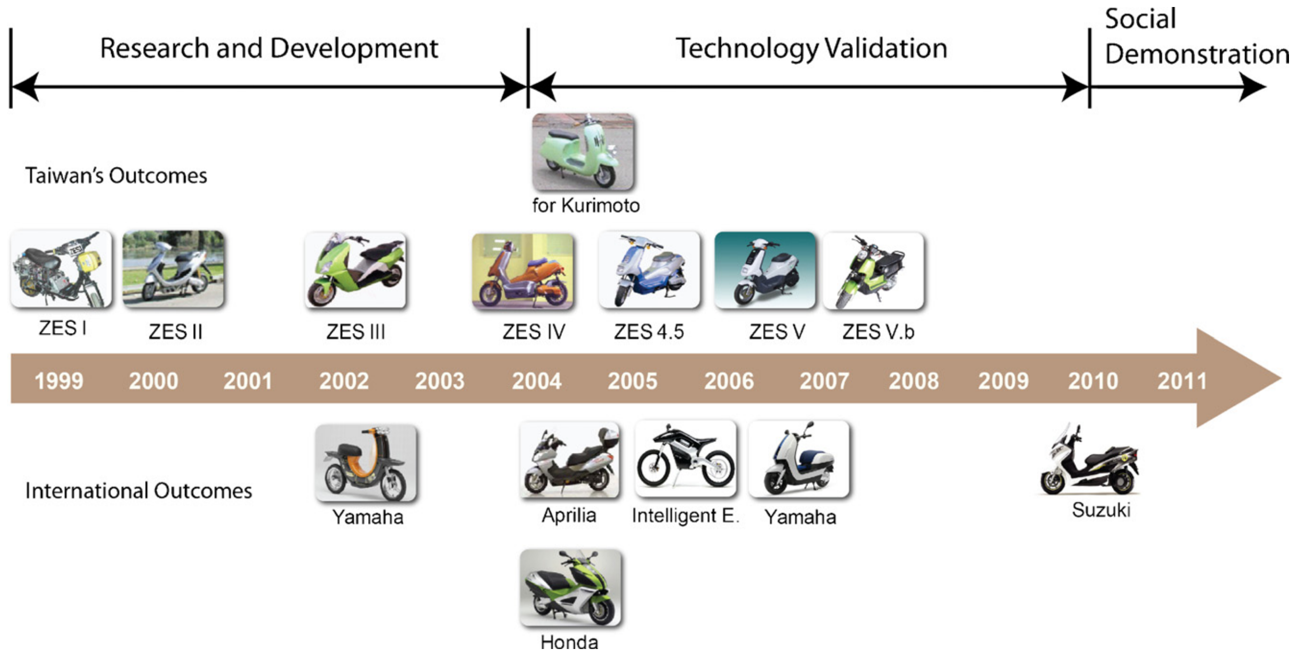

Fig. 9. Comparison of timeline for developing the fuel cell scooter in Taiwan and in the world.

As indicated in Fig. 9, the first prototype of a fuel cell scooter ZES I in the world was built in 1999; it was remodeled from an existing battery powered scooter [48,49]. All components of the fuel cell engine were purchased from commercially available sources. Obviously, almost all components, including the 3.0 kW PEM fuel cell stack [50], were bulky and not designed for optimal scooter integration. ZES I was tested at the Automotive Research and Testing Center (ARTC) in Taiwan and, as expected, its performance was not spectacular, mainly because of poor stack output power. Nevertheless, ZES I fulfilled its purpose of demonstrating the applicability and feasibility of fuel cell technology to scooters. In October 2000, Asia Pacific Fuel Cell Technologies Ltd. (APFCT) completed the construction of its second-generation fuel cell scooter (ZES II). ZES II was equipped with a specially designed ambient pressure PEM fuel cell stack and a metal hydride hydrogen supply system. The chassis of a battery-powered electric scooter was modified for using it in the fuel cell scooter. Although ZES II was not as functional as the existing ICE scooters, it showed the commercial potential of the application of fuel cell technology to scooters. Subsequently, the third-generation fuel cell scooter ZES III was unveiled in 2002. It has a new design obtained by integrating a fuel cell engine with a scooter chassis from ground-up. The modern European styling of the scooter complements its advanced fuel cell engine technology. It matches the fuel cell engine with the drive train. However, the performance does not match the expected targets, especially for a heavy weight (>100 kg). Moreover, its durability needs to be improved. Thereafter, the production of commercial models of the fuel cell scooters ZES IV and ZES V commenced in 2005 and 2007, respectively. ZES V is powered by a hybrid scheme with a new 1.3 kW fuel cell stack, which increases the driving range of its predecessor by 33%, from 60 km (37 miles) to 80 km (50 miles), and supports a slightly higher top speed of 60 km/h (37 mph), compared to 52 km/h (32 mph) for the prior generation. Detailed specifications of ZES V are shown in Table 2.

During 2005–2010, technology validation and demonstration of fuel cell scooters were carried out extensively on the island by the manufacturers themselves [51–54]. For example, fuel cell scooters have been provided to their employees for their daily commute. In addition, several fuel cell scooters have also been provided to the Campus Patrols of National Tsing Hua University in Taiwan, as well as to the police office of the Hsinchu Science-based Park in Taiwan for patrol purposes [53]. Most importantly, in 2010, the fuel cell scooters were tested in different weather and road conditions around Taiwan [54], and they covered more than 1000 km in a four-day trip. This event marks the first instance of a long-distance on-road test drive of fuel cell scooters in the world. As shown in Fig. 10, during the trip, fuel cell scooters encountered different severe weather conditions, including hot weather with strong sunlight for hours and heavy showers. However, the fuel cell system operated smoothly and the performance of the scooter remained stable throughout the trip. The trip demonstrated the maturity, durability, and stability of the fuel cell system and integration technology.

4.2. Demonstration program in Taiwan

To avoid pitfalls faced in the past in the promotion of rechargeable-battery driven scooters [55] and LPG-fueled taxis [56] in Taiwan, an aggressive demonstration should be given due consideration, before the commercialization of fuel cell scooters.

Recently, the learning demonstration program for fuel cell scooters in parallel with the hydrogen infrastructure in real-world conditions was planned under the "National Science and Technology Program on Energy" in Taiwan. The program tests, validates, and demonstrates the whole range of solutions for fuel cell scooters, which involve domestic fuel cell technologies, metal hydride hydrogen storage, and the hydrogen infrastructure model. In contrast to the early technology validation and demonstration carried out by the manufactures, the learning demonstration will be carried out independently by third parties that gathers and analyzes data from fuel cell scooters in real-world conditions, and then compares the results to pre-set technical targets. The results of these programs are expected to help policy makers in making decisions pertaining to the commercialization of the fuel cell scooters industry. Another important objective of the learning demonstration program is to help identify codes and standards that will be necessary and useful for the commercialization of fuel cell scooters. In addition, via the learning demonstration program, information

Fig. 10. Technology validation of fuel cell scooter in a 1000 km trip around Taiwan, (a) fleet of fuel cell scooter, (b) dashboard of fuel cell scoter, (c) standby on the road, (d) driving in a heavy rain, and (e) and (f) replacement of fuel canister.

about users' perceptions and their experience in driving fuel cell scooters would be collected. The program would signify a milestone in the commercialization of fuel cell scooters in Taiwan.

According to the learning demonstration program, a fleet of 100 fuel cell scooters subsidized by the Bureau of Energy (BOE), Taiwan, will be acquired in early 2012, and then the fleet demonstration will begin. The fuel cell scooters will be used in different areas and under different scenarios representing daily usage. The fleet will be centrally controlled, similar to the case of the vehicle fleet used for newspaper, mail, and milk delivery, because such control will make it easy to manage the fleet and secure the safety of the hydrogen and fuel cells. Fig. 11 shows the design and evaluation methodologies for fleet control and data collection in the learning demonstration of fuel cell scooters. The program will be carried out in cities with urban traffic, such as the cities of Taipei and Tainan. For the learning demonstration program, an integrated driving recorder has been developed to record all driving data and wirelessly transmit the data to a remote web server. Faults in the scooters and malfunctioning of the scooter can be detected quickly, thereby preventing disasters. The program also proposes a Web-based, real-time calculation system, such as LabVIEW, as the end user interface [57], as shown in Fig. 12. Real-time experimental results have shown that the proposed validation strategy is stable and reliable. Furthermore, it can also assist in improving the traffic flow in the surrounding areas. All the results of the test have pointed out that the proposed web-based evaluation system is cost-effective and shows a quick

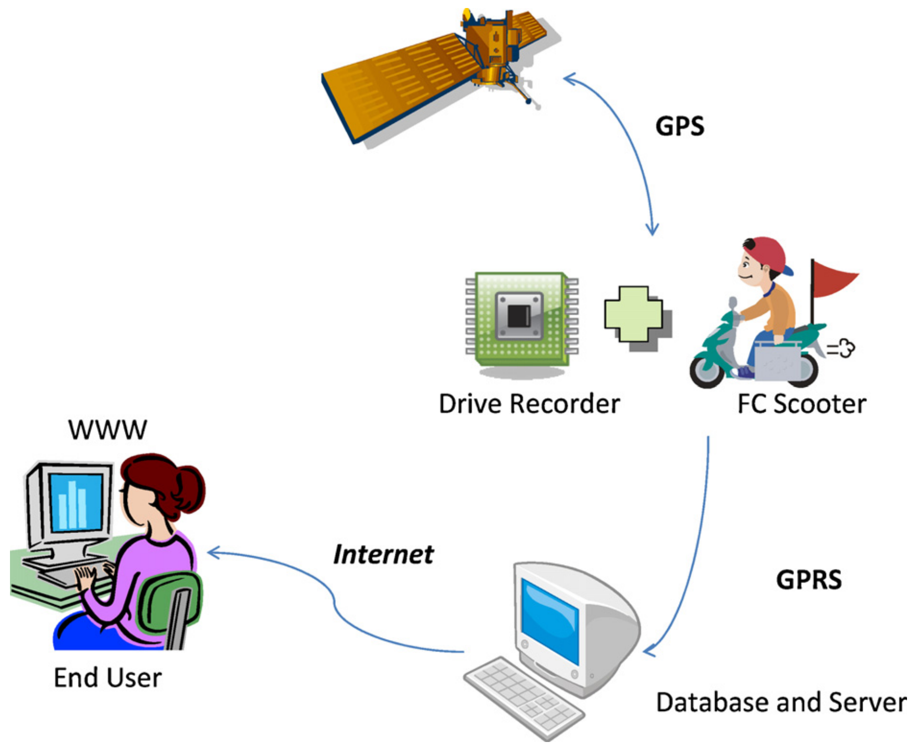

Fig. 11. Proposed real-time monitoring system for learning demonstration of fuel cell scooters in Taiwan.

response when used for evaluating a new generation of urban vehicles. The period of the learning demonstration is estimated to be about one year.

After finishing the demonstration program successfully, the fuel cell scooters would be ready to enter the market, According to estimates of the manufacturers, when the annual production output reaches 100,000 units, the estimated selling price of each fuel cell scooter will be about US$ 2200. When the output doubles, the estimated price is expected to drop to about US$ 1730, roughly the current market price of a 125 cc scooter. The scooter's design and performance will be comparable to those of conventional gasoline-engine scooters and it would be competitively priced [58].

4.3. Environmental aspects

The fuel cell vehicles would have the benefits of reducing the GHG emission and improving the energy conservation in the transport sector. In the present work, the GREET (greenhouse gases, regulated emissions, and energy use in transportation) model developed by Argonne National Laboratory (ANL) was employed to examine the life-cycle energy and emission of various scooter technologies and transportation fuels. This model has been widely applied to provide well-to-wheels (WTWs) results for various vehicles/fuel combinations [30,59–63]. It was herein modified to conduct a WTW analysis of the fuel cell scooters. Fig. 13(a) gives a comparison of the energy density (Wh/km) for three types of scooters, i.e., ICE scooters, battery electric scooters, and fuel cell scooters. It was seen from this figure that the battery electric scooter consumed most energy during the fuel operation (WTT stage) among the three types of scooters. It is reasonable because the WTT efficiency of electricity mix for charging the battery of electric scooters was significantly lower than that of the hydrogen produced from the nature-gas (NG) steam reformer and that of the gasoline produced from the refinery process. Fortunately, the battery electric scooter largely cut the energy consumption during the scooter operation (TTW stage), which reduced its total energy density. Fig. 13(b) further compared the GHG emission among the three types of scooters. The GHG emissions for both battery electric scooters and fuel cell scooters were zero on the road. Therefore, the total GHG emission for both zero emission scooters was largely lower than that of the ICE scooter. The contribution of reduction in GHG emission and total energy usage by replacing the ICE scooters by the zero-emission scooters was depicted in Fig. 14. Both zero-emission scooters had the advantage in the GHG-emission reduction and energy conservation. The NG-based hydrogen fuel cell scooters had the best performance by reducing the energy usage and the GHG emission up to 35% and 58%, respectively. Therefore, the fuel cell scooters fueled with hydrogen was most promised for sustainable transportation due to their great benefit in energy saving and GHG-emission reduction.

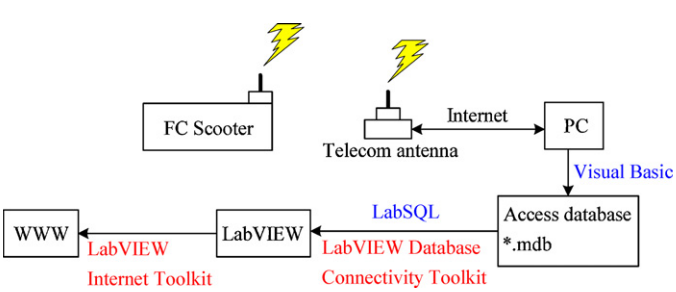

Fig. 12. Interface and platform employed for information publishing.

4.4. SWOT analysis

Among all countries, Taiwan has one of the highest population densities in the world. People do not live far away from their working place, and therefore scooters have become a popular means of personal transport for commuting to the workplace. The annual

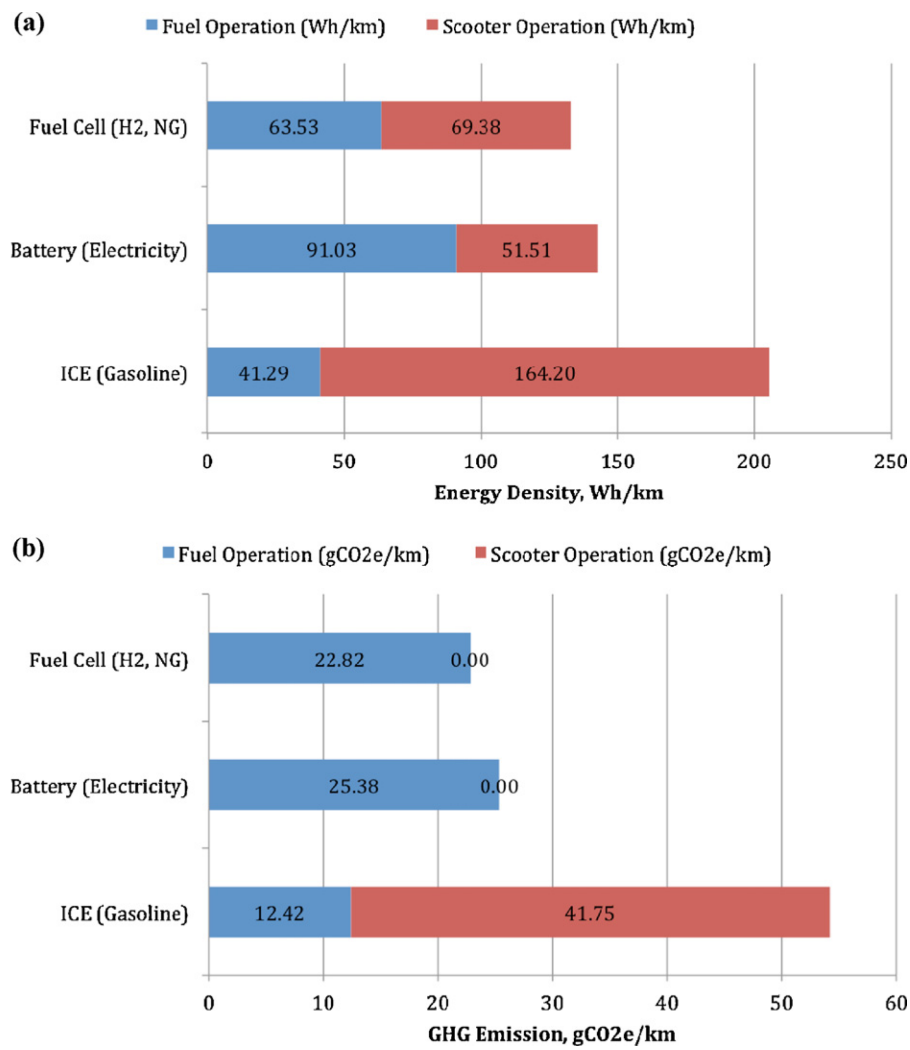

Fig. 13. Comparison of energy density (a) and GHG emission (b) among three types of scooters.

domestic market size of the scooters (ICE) was about 300,000, which could be the market size of fuel cell scooters if the scooters were to be commercialized successfully in Taiwan. The size of the potential global market would be much larger. The SWOT (strengths, weaknesses, opportunities, and threats) analysis for Taiwan for the development of fuel cell scooters was described below.

4.4.1. Strengths

With enormous efforts put in over the last 50 years, the scooter industry in Taiwan has developed successfully. It has a solid foundation because of a strong electronic and mechanical industrial base, mature management capability, and most importantly, abundant expertise. In addition, Taiwan has plenty of experience in developing rechargeable-battery-powered electric scooters. Therefore,

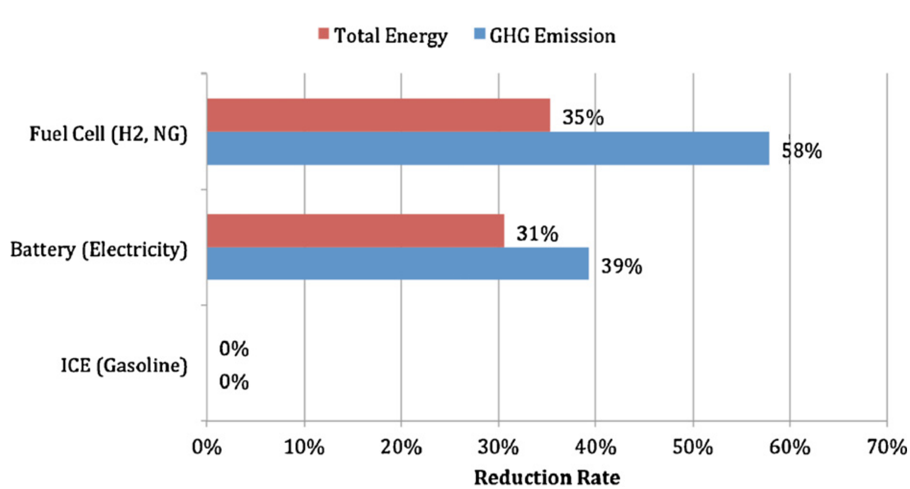

Fig. 14. Reduction rate in total energy and GHG emission for zero emission scooter as compared to the ICE scooter.

the fuel cell scooter would be a strategic target in the next stage of the promotion of zero-emission scooters. Thus, the development of fuel cell scooters is not only intended for shifting to zero-emission vehicles, but also for expanding the sales channels by exploiting the reputation of the country as the “Kingdom of Scooter Manufacturers” for promoting fuel cell scooters in the global market.

4.4.2. Weaknesses

The infrastructure for initially refilling (exchanging) hydrogen fuel (metal hydride canisters) has not yet been established and thus, considerable financial support and manpower are needed for its development. Considerable efforts need to be put in for educating the general public regarding about the use of hydrogen as an energy source for fuel cell scooters. The production cost of fuel cell scooters would be high owing to the limited number of suppliers of the required material and components. In addition, the labor costs would be high because of the lack of skilled labor. Therefore, the fuel cell scooters cannot compete against the conventional ICE scooters in terms of cost in the short term. Therefore, when the fuel cell scooters are launched, they will need governmental subsidies for competing with the conventional ICE scooters.

4.4.3. Opportunities

Demographics, social and economic forces have aligned to encourage market growth of electric scooters. Countries in the Asia Pacific region like China, Taiwan, and Vietnam, continue to account for the vast majority of electric scooter sales in recent years, while the fastest growth occurs in the Middle East, Latin America, and North America. According to a recent report from Pike Research [64], worldwide sales of electric two-wheel vehicles are expected to increase at a compound annual growth rate (CAGR) of 9.4% through 2016. However, the electric scooters powered by the rechargeable battery still face the challenges of prices, safety, and recharging time. In the sustainable transport strategy of Taiwan, the fuel cell scooters are regarded as the next option after the rechargeable battery electric scooters for personal commuting. Actually, the Taiwan government has been supporting the promotion of fuel cell scooters for many years. To the best of the author’s knowledge, to date there has been no other government-supported program for the development of fuel cell scooters in the world. In order to commercialize fuel cell scooters, related codes and standards are being developed actively. If it can develop a successful business model, Taiwan would enjoy the advantages of tapping the huge global market for zero-emission scooters.

4.4.4. Threats

As mentioned before, the major automakers are deeply involved in the development of fuel cell sedans. Actually, some of them, such as Honda, have also produced gasoline-propelled engine scooters. Taiwanese companies will face a serious threat if the automakers, by applying their vehicular technology on scooters, launch fuel cell scooters. Owing to the availability of cheap labor and the fast growing scooter industry, China has a cost advantage over Taiwan. In addition, the counterfeiting capability of China poses a threat to the development of fuel cell scooters. Additionally, although both the functions and effectiveness of battery-powered electric scooters are not as good as those of fuel cell scooters, the former scooter is still a potential competitor with technology breakthroughs being made with regard to the battery-recharging time and the storage capacity.

5. Conclusion

A comprehensive review of the development of fuel cell scooters has been provided. Major findings were summarized below.

1. The technical feasibility of fuel cell scooters in Taiwan has been proved, including the key technologies used in fuel cell engines and the hydrogen infrastructure model.
2. Changing petrol scooters to hydrogen fuel cell scooters would provide tangible benefits in terms of reducing GHG emission, improving energy conservation, and lessening dependence on imported petroleum. Results showed that the contribution of replacing petrol scooters by hydrogen fuel cell scooters to the reduction in greenhouse gas emission and the improvement in energy efficiency were about 58% and 35%, respectively.
3. From the SWOT analysis of Taiwan’s competitiveness in the global market, Taiwan has a strong reason for developing fuel cell scooters. First, its traditional scooter industry is extremely competitive worldwide. Then, Taiwan has plenty of experience in developing rechargeable-battery-powered electric scooters. Therefore, the fuel cell scooter would be a strategic target in the next stage of the promotion of zero-emission scooters.
4. With mature fuel cell technology together with solid foundation of the scooter industry, Taiwan is on the verge of pre-commercialization learning demonstration of fuel cell scooters along with the corresponding hydrogen infrastructure. If it can develop a successful business model, Taiwan will begin the process of tapping the huge domestic and global markets for zero-emission scooters.

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